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RELATION BETWEEN MOISTURE CONTENT OF SAND AND CRITICAL WIND VELOCITY AT WHICH SAND GRAINS BEGIN TO MOVE

Masuji Akiba

Translation of "Sado gansuiryō to hisha genkai fūsokudo to no kankei," Nōgyō doboku kenkyū, Vol. 5, No. 2, pp. 157-174
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16. Abstract

The relations existing between the critical wind velocity at which sand grains begin to move, and the size, weight and frictional and adhesive forces of the sand grains are given. Frictional and adhesive forces of grains vary not only according to the properties and conditions of soils, but also according to their moisture content. This includes a definite correlation between the moisture content of sand and critical wind velocity at which sand grains move; relations exist between the moisture content at critical points of sand movement and the force of frictional adhesion and grains; a determination of the practical values of the findings with respect to measures for the prevention of blown sand is made.

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TABLE OF CONTENTS

RELATION BETWEEN MOISTURE CONTENT OF SAND AND CRITICAL WIND VELOCITY AT WHICH SAND GRAINS BEGIN TO MOVE

Masuji Akiba

I. General Theory

Earlier, the writer prescribed dynamically the relations /157*
existing between the critical wind velocity at which sand grains begin to move, and the size, weight, and frictional and adhesive force of grains are known to vary not only according to the properties and conditions of soils, but also according to their moisture content. With such soils as clay which exhibit a grouped granular formation in the dry state, the scattering of grains is unlikely to occur unless this grouped granular condition is broken down. With sand, however, the exposure in the dry state to suitable wind velocity would result in immediate scattering since the individual grains are always able to move independently.

From the standpoint of land improvement with respect to sandy terrains, sand arrestation and irrigation and drainage are among the aspects which cannot be ignored under any circumstance. In view of both of these aspects, it is believed that it would not be a wasted effort to attempt to clarify the relation between the sand moisture content and the critical wind velocity at which the sand grains begin to move. However, what will be presented in this report is the summary of only experimental results obtained in the laboratory rather than from outdoor experiments, so that there would be a risk in applying these finds directly to natural conditions. It is hoped that these results from the laboratory may provide hints for the formulation of measures for the improvement of sandy terrains, and serve as a guide for the preparation of practical and concrete plans in the future.

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*Numbers in the margins indicate pagination in the foreign text.

For this report, the experiment was conducted with the following objectives.

1. To determine whether or not there exists a definite correlation between the moisture content of sand and the critical wind velocity at which the sand grains begin to move. And to describe this relation in concrete terms if such a correlation does exist.

2. To determine, if objective (1) is proven valid, what kinds of relations exist between the moisture content at the critical point of sand movement, and the force of frictional adhesion and the grains.

3. To explore the time curves up to the occurrence of the blown sand phenomenon by exposing sand samples of the same initial moisture content to wind.

4. The determination of the practical values of the findings with respect to measures for the prevention of blown sand.

II. Experimental values

The sand sample was collected from sand dunes at the village of Ikeshinden in Shizuoka Prefecture. Its specific gravity was 2.7, while the gram sizes ranged from 0.1 to 0.5 mm. For sand containers, circular cylinders 3 cm in diameter were used /158
throughout with the following exception. For a preliminary test in the initial stage of the experiment, the use of containers was avoided when sand of a given moisture content was lumped and placed on a glass plate where it was exposed to the wind. However, a cylinder 3 cm in diameter and 0.5 cm in height was eventually used with this sample. The test in question was completed by repeating the above procedure twice.

The water was added in the following manner. Equal amounts of sand were placed in containers of the same shape, and equal quantities of water were added with a pipette until the samples were almost saturated, after the sand surfaces had first been leveled by tapping the edges of the containers several times. The sand samples exhibited practically identical conditions of subsidence and compression after this treatment.

For the amounts of water added, such percentages as 20%, 22%, 24%, 25% and 27.25% by weight were selected, but it was found to be difficult to obtain uniform permeation in the case of smaller amounts of water.

Two methods were used in the arrangement of the containers. In one method, the containers were placed in front of the blower at the same time and at regular intervals so that the wind velocity would vary from position to position. In the instant that the sand began to fly off, the moisture contents were measured and a correlation was sought between the wind velocities and the moisture contents. In the other method, the distances and the wind velocity were varied while the containers were arranged in fixed positions, and the moisture contents in the moment the sand was scattered were studied.

In terms of the measuring instruments, a Biram [illegible] anemometer and a tachometer were used for the wind velocity, while a chemical balance, an electric fixed-temperature drier and a cooling drier were used for the moisture content.

The following procedure was adopted for the measurement of the moisture content. As mentioned above, identical quantities of water are added to the sand in the containers which are then arranged in place and surveyed continuously as specified wind velocity is applied. The normal scattering pattern of sand is that after the first grain flies off, the stage of vigorous scattering is reached in the short duration of 2-3 minutes. For this reason, if the proper timing is lost, the experiment may be invalidated. Consequently, the sand is removed from the containers after a standard interval of about 1.5 minutes from the initial scattering. The sand is transferred to separately-provided small bottles which are then capped and weighed on the balance. Next, the bottles are placed inside the electric fixed-temperature drier where they are heated at 100°C-110°C for 8-12 hours. The bottles are taken out and placed in the cooling drier for several hours after which they are reweighed. The weight difference before and after drying was adopted as the moisture content at the time of scattering, and it was decided to express the moisture contents in terms of the weight percentage of the dry sand.

The intervals from the initial application of wind to the scattering of the sand were timed with a stop watch, while the wind velocities were determined by means of the Biram [?] anemometer and the tachometer.

In addition, the temperature, the humidity and the weather condition were also surveyed and recorded.

III. Observation

(Procedure) The measurements were conducted during appropriate moments in the daytime in the period from mid-July, 1931 to the end of January, 1932.

The reasons the observation period was scheduled to more or less span the two seasons of summer and winter was that it was assumed that if meteorological conditions could make a significant difference in the relation between the sand moisture content and the critical wind velocity at which sand grains begin to move, the effect on this relation would be more pronounced with respect to meteorological differences between summer and winter.

When sand in the containers are first given identical moisture contents and then exposed to different wind velocities, it is to be expected that a variance would occur in the time durations up to the occurrence of the scattering of the sand. Thus, when the starting point is unified for all the containers, the time durations up to the occurrence of the blown sand phenomenon would vary between the containers. It is thus //159
difficult to keep the meteorological conditions absolutely identical for all the containers during the observation period. The moisture content of the sand in the instant of scattering tends to be low in the part close to the surface of the sand and become higher with increasing depth. A few examples taken from the author's experimental findings are given in the table below.

Date: 1/16/1932

Wind velocity (m/sec)		13.0	9.9	8.0	5.65
Moisture content	Top %	2.105	1.935	1.224	0.9370
	Bottom%	2.557	2.494	1.923	1.5630
	Average %	2.459	2.337	1.666	1.3130

Date: 1/18/1932

Wind velocity (m/sec)		12.9	10.25	7.85	5.88	4.35
Moisture content	Top %	2.854	2.308	1.215	0.6607	0.3849
	Bottom%%	3.107	2.569	1.757	1.3150	0.6180
	Average %	2.985	2.448	1.546	1.0350	0.5196

The above tables signify that the evaporation effect due to the wind velocity is always major near the surface and diminishes as the depth increases. The author would like to discuss this aspect in detail on another occasion.

In view of the above phenomenon, effort was made in this experiment to establish the average moisture level, but due to time requirements, the collection of the sandy soil deposited on the bottom and the side of the containers was limited to that which could be collected easily with a spoon.

As far as the determination of the critical sand scattering point is concerned, accurate experimental results are difficult to obtain as it is easily influenced by subjective factors. The decision over whether to consider the take-off of the first grain as the point of criticality, or to define the latter as the moment at which the sand grains over the entire surface are scattered proved troublesome, but it was decided that the point would be defined on an empirical basis in this experiment in the following manner. The point of criticality was defined as the instance in which the scattering phenomenon occurred more or less over the total surface and continuously after the take-off of the first grain. This limit occurs within 1.5 minutes of the take-off of the first grain.

As indicated by the above, the technique of the experimental procedure has a major bearing on the results in the case of this experiment. Thus, apparent errors contained in the experimental results given below may be due to defects in the procedure.

(Results) The recorded results were of numerical values shown in separate tables (see Appended Tables A, B, and C). In other words, the critical wind velocities applied ranged between 16.5 and 4.5 m/sec, and the moisture contents for this range were less than 3.5%. There is a relatively consistent relation between this critical wind velocity at which the sand is scattered and the moisture content. It is observed at once that the relationship is linear, which is to say the critical wind velocity is directly proportional to the moisture content.

The next question is how much time is required for the blown sand phenomenon to occur when sand of a fixed moisture content is exposed to a fixed wind velocity. From the tables, it may be assumed that there is a fairly consistent relation. The fact that as the wind velocity used becomes greater, the advent of the blown sand phenomenon becomes sooner obviously agrees with the general supposition. As evident in the appended figures, the relational lines of velocity vs. time form consistent curves.

IV. Discussion

(1.) From the author's experimental results, it was possible to determine that there is a clear correlation between the sand moisture content and the critical wind velocity at which sand grains begin to move. Discussions on this subject are quite rare, however. In Japan, there was once a research report from Professor Hara [1] of the Tottori Agricultural School /160
[Tottori Kōnō], but it did not go as far as the clear indication of a correlation. The author plotted his experimental results on graphs, and because they were approximately linear, he was able to obtain many linear equations by the method of least squares as shown in the appended tables. The comparison between the measured results from each of the trials and the /161
calculated results from the linear equations does not show any major differences. But since there would be differences with respect to not only meteorological conditions such as temperature but also procedural factors between different days, it would not be reasonable to summarize these results into a single formula, at least not until their functional relations are clarified. But it can be readily acknowledged that when all of the experimental results are plotted together for the purposes of determining the general outline, an approximately linear relationship is obtained. It is subsequently noted that there are two systems, namely a straight line with a very steep slope

and another with a slope a little milder as shown in Fig. 1 and Fig. 2.

To put it simply, they are all in the interval of a = 5 ~ 10 with the exception of a few cases represented by the following linear equation.

$$\boxed{W = a\alpha + b} \qquad (1)$$

where W = critical wind velocity (m/sec)
α = moisture content % at critical sand scattering point
a,b = coefficients variable according to climate and procedure

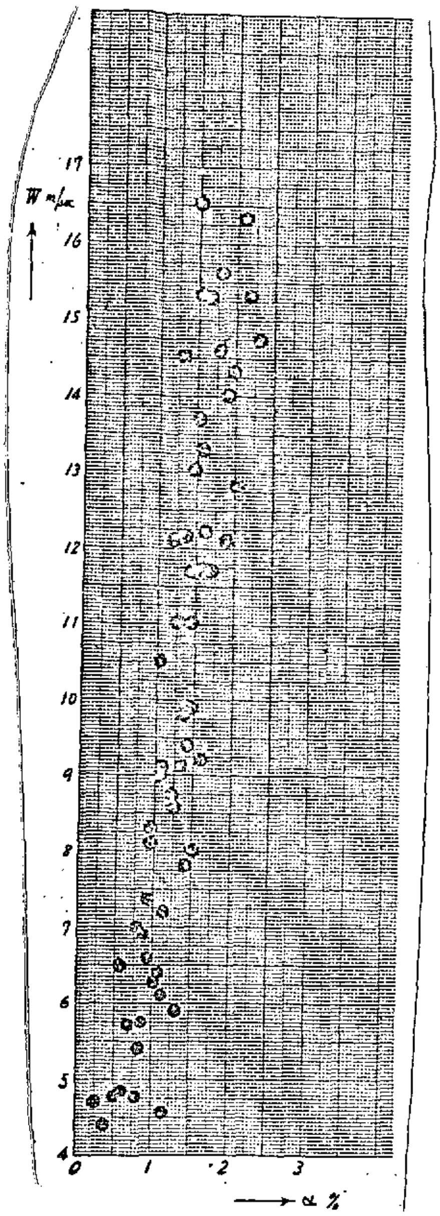


Fig. 1.

It may seem valid to consider the critical sand scattering wind velocity as W = b when α = 0 in Eq. (1) which is to say the state of absolute dryness. But this is in fact untrue as the moisture content (α) represents the average moisture content from the sand surface to a certain depth so that b cannot represent the critical sand scattering wind velocity for the absolutely for the absolutely dry state. It is noted that the moisture content varies between the surface layer and the bottom layer, as mentioned earlier, when evaporation occurs on the sand surface due to wind exposure, with the content increasing with depth. Thus what is termed the moisture content at the critical sand scattering point in this experiment is in the end only the average content (in most cases the content at the depth of 3 mm from the surface). In order to determine the moisture condition at the surface, the following method may be used for an approximate answer.

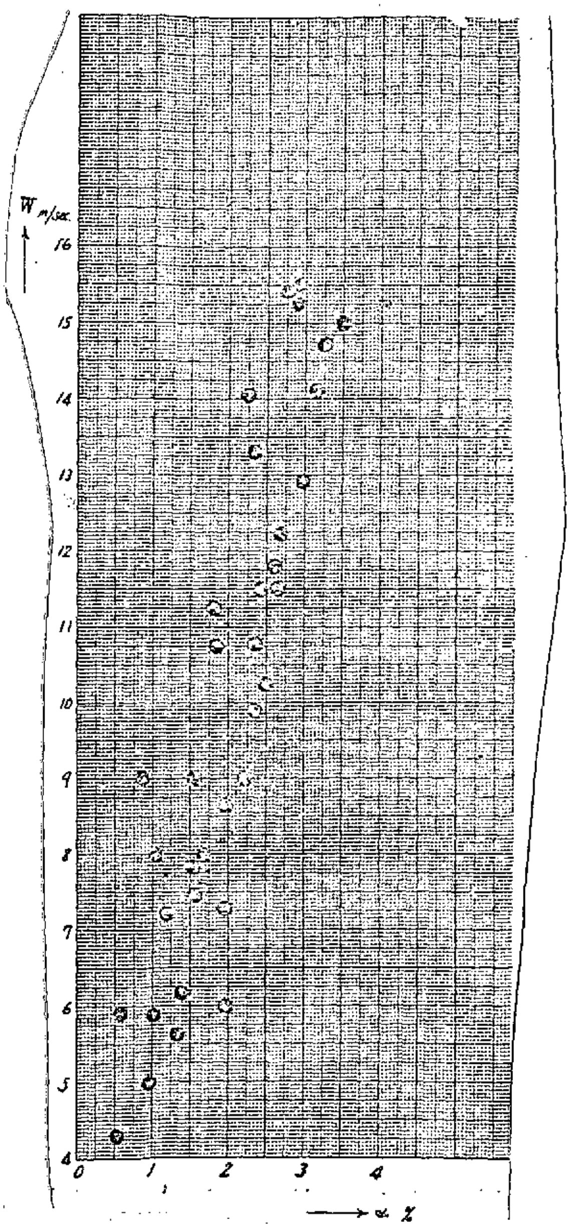


Fig. 2.

A separate sample of absolutely dry sand is exposed to the blower, and the critical wind velocity in this case is assumed to be (b_1). By extending (b_1) along the W axis as far as y_1 and by drawing straight line N from this point parallel to straight line M which is $W = a\alpha + b$, N becomes the approximate equation expressing roughly the relation between the moisture content of the surface layer and the critical wind velocity at which the sand grains begin to move (see Fig. 3.)

$$W = a\alpha_1 + b_1 \qquad (2)$$

While the values of (a) in Eq. 1 mostly range from 3.5 to 9, so that the median figure would be around 6 or 5 and fairly constant, the variation of the values of (b) is relatively wide. This result must be partly due to the method used for collecting the sand samples from the containers, but it is also conceivable that due to the nonuniformity of the meteorological and the

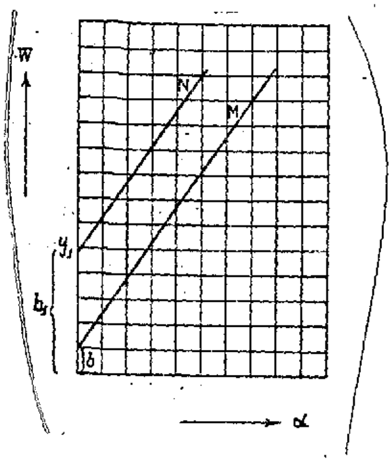


Fig. 3.

soil conditions, the circumstances of evaporation varied according to the depth causing an uneven distribution of moisture in the sand.

At any rate, an accurate exploration of Eq. (1) would provide useful material for estimating the relation between moisture at the sand surface and the critical wind velocity at which the sand grains begin to move. It would probably provide practical hints for the purpose of blown sand carrestation.

(2.) Let us now examine the force of frictional adhesion for sand of fixed grain size and /162 fixed specific gravity as mentioned above, and then briefly consider the cases of varying grain sizes and specific gravities.

It is generally recognized that within a certain limit an increase in the moisture content is accompanied by an increase in the force of frictional adhesion. However, the latter decreases in contrast beyond a certain limit [2].

At this point, a deliberation will be attempted concerning the process of the variation of frictional adhesion which accompanies changes in the moisture content on the basis of the author's experimental findings. When the moisture content is low, a situation can be imagined in which water adheres in an annular manner solely around the point of contact of the grains. In such a case, the grains are attracted toward each other by the surface tension of this film of water. This This force of attraction (P) can be obtained by the following equation.

$$P = c_1 T\left(\frac{1}{r_1} - \frac{1}{r_2}\right) + c_2 P_1 \qquad (3)$$

where r_1 and r_2 are the radii of curvature in the directions of the two principal axes on the surface of the water adhering to the sand grains. T is the surface tension of the water, while P_1 is the force acting between the water, and air and the sand grains.

In the condition illustrated by Fig. 4,

$$r_1 = r(\sec\theta - 1); \quad r_2 = r(1 + \tan\theta - \sec\theta); \quad P_1 = \varphi(\theta)$$
$$\therefore\ P = c_1 \frac{T}{r} \cdot \frac{(2\sec\theta - \tan\theta - 2)}{(1 + \tan\theta - \sec\theta)(\sec\theta - 1)} + c_2\varphi(\theta) \cdots \qquad (4)$$

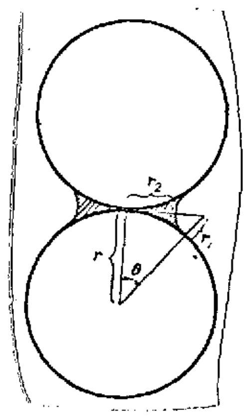


Fig. 4.

Letting (n) be the number of points at which a single grain is in contact with other grains, the force with which this grain is attracted, which is to say the adhesive force (P_c) due to the presence of moisture can be calculated approximately by

$$P_c = n c_3 P_1 \qquad (5)$$

In other words, the above relation is clarified automatically once the functional relation between (θ) and the moisture content is explained. Mr. W. B. Haines [3] attempted such a procedure (although with an equation slightly different from the equation above) and tried, at the same time, to support it experimentally. He obtained a type of a parabolic curve, but this was still insufficient.

Mr. Fischer improved on Mr. Haines' equation and published an equation similar to Eq. (4), as well as a relational equation for θ and moisture content (α). When this author used this equation for calculation from data regarding oil rupture [4], an approximate result of $P_c = c_1^{0.5}$ was obtained. Although this is a parabolic relation as in the case of calculation from the wind velocity to be mentioned later, the index shows a wide deviation. This is probably the result of differences in terms of wind velocity drag, as well as pressure, temperature and pther aspects of the film of water.

As far as the author's experimental findings are concerned, it is also possible to consider the frictional drag with respect to the wind, apart from the adhesive force. Letting (P_W) be the total drag with respect to the wind and (f) be the frictional and adhesive force, we get

$$P_W = K'f \qquad W^2 = K'' P_W = \tag{6}$$

but since /163

$$W = \sqrt{u\rho r} \qquad W = K_1'' P_W^{\frac{1}{2}} \tag{6_1}$$

$$f \propto Y$$

$$W = K f^{\frac{1}{2}} \tag{6_2}$$

where W is the wind velocity in m/sec.

From Eqs. (1) and $(6)_2$, we get

$$\alpha = k_1 + k_2 f^{\frac{1}{2}} \quad \text{or} \quad f = A + B\alpha + C\alpha^2 \tag{7}$$

In other words, the relation indicates a type of parabolic curve. This should lead to the discussion of the relationship between Eq. (4) and Eq. (7), but this will be left for another occasion. For the time being, it suffices to describe the certain amount of increase in the sum of the friction and the adhesive power accompanying an increase in the sand moisture content by means of the above equation. Thus, $\alpha = 0$ would indicate the case of dry sand and A would represent solely the frictional force. Also, although the relation between the grain size and the wind velocity, $W = cr^{0.5}$, was published on a theoretical basis without experimental evidence, recent experimental results obtained by the author indicate that it is more or less correct. The writer intends to publish these results eventually, but at any rate, since the power exponent of 1/2 is an approximate value which was calculated for an ideal grain, it had to be confirmed through experimentation that values in the vicinity of 1/2 could be adopted.

When both the grain size and the specific gravity vary, it is hardly possible to reach immediate conclusions through Eqs. (1) and (2). But in general terms, it is possible to infer that within a certain limit an increase in the moisture content would make the critical sand scattering wind velocity greater regardless of the grain size. But this must be subjected to some adjustments on the basis of the experimental study of Eq. (2).

(3.) The time durations required for sand samples of identical initial moisture contents to be scattered would vary according to the magnitude of the wind velocity. The time curve with the wind velocity as the vertical axis and time as the horizontal axis assumed the following fixed formula. It is

$$W = \frac{K_1}{T^m} + K_2 \qquad (8)$$

where W = wind velocity in m/sec, T = time (minutes), and m, K_1 and K_2 the various coefficients. While m and K_1 are dependent on the climate to assume high values when low humidity and high temperature occur concurrently, K_2 is a coefficient which is affected by the grain size and specific gravity of the sand.

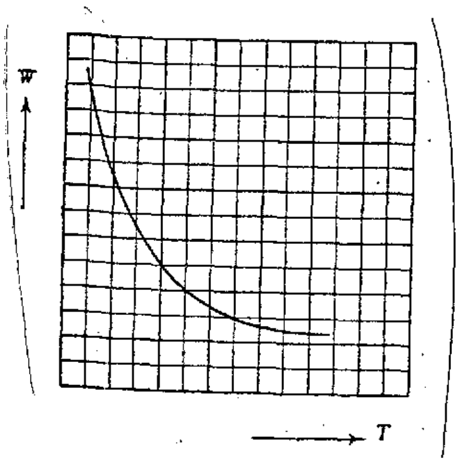


Fig. 5.

In Eq. (4), when $T = 0$, $W = \infty$. This signifies that the critical wind velocity for which the time duration becomes 0 must be infi infinitely large. Also, when $T = \infty$, $W = K_2$. When sand is /164 exposed to wind over an extremely long period of time, the moisture would be completely evaporated so that the moisture content should become 0, but because of atmospheric humidity and adsorbed moisture, a certain amount of moisture is inevitable. Therefore, K_2 represents the sand scattering wind velocity in cases where the sand moisture content is close to zero. In practice, the above fact does not seem irrational. K_2 should thus take a value which is approximately that of b_1 in Eq. (2). It should be noted that in the case of natural sand, the process of the compensation of moisture loss due to evaporation through the capillary phenomenon is at variance with the procedure of this experiment. Thus the time curve would also require due considerations.

The experimental results of Appended Tables [C] only serve to corroborate the general validity of Eq. (4). K_2 would thus be no longer equal to b_1, but only a numerical value which is close to b_1. Examining the coefficients of Eq. (4) in the [C] Tables, it is seen that $m = 0.72$-1.032, $K_1 = 200$-1200, and $K_2 = 1$-2.5. When the logarithm of the experimental results is plotted, the curve does not form a strict straight line but the margin of error is relatively small, so that Eq. (4) is sufficient for determining the approximate relationship. Climatic conditions also influence the time curve of the blown sand

sand. For example, a low temperature with a high humidity causes a prolongation of the time duration required for the sand to scatter, while a high temperature with a low humidity causes the reduction of this duration. This is determined by comparing the Appended Tables $[A]^{(I)}_{10}$ and $[A]^{(I)}_{11}$ which are about the same in temperature but widely divergent in humidity, as well as comparing the Tables $[A]_{12}$ and $[B]_1$ which are about the same in humidity but widely divergent in temperature. In addition, the effects of humidity and temperature on the time curve are very great when the wind velocity is low, and show a tendency to diminish as the wind velocity becomes higher. In other words, at high wind velocities only the wind velocity has a major effect with the other factors having no marked effects (see Appended Figures and Appended Tables $[C]_2$, $[C]_4$, $[C]_5$ and $[C]_{10}$).

[Translator's note: It is strongly suspected that all references to Eq. (4) in Section 3 should, in fact, be references to Eq. (8).]

4. The practical values of the findings discussed so far are considered at this point with respect to preventive measures against blown sand. From the author's experiment, it was learned that the blow sand phenomenon does not occur in the case of sand containing slight amounts of moisture. Furthermore, it was observed that a more or less constant linear relation with a steep slope existed between the mosture content and the critical wind velocity at which sand grains begin to move.

The above relationship becomes more applicable as the sand grain form approaches the spherical shape. Therefore, sand from coastal sand terrains would meet this condition since corners of such sand grains are eroded and rounded through the drift sand and quicksand phenomena. According to the author's experiments, clay soils are not suitable for the application of Eq. (1) because even when moisture is removed through evaporation the

the grains would combine to form a grouped granular body. Also, with such substances as powdered glass in which the corners of the grains are sharp rather than rounded, the grains cohere with each other to exhibit a condition resembling that of a grouped granular body so that again, the relation of Eq. (1) is unlikely to occur. However, even with substances like clay soil and powdered glass, if a force strong enough to break down the grain grouping is exerted the grains would scatter immediately. In the case of the sandy dust raised by gusts of wind in the Kantō Plain in early spring, therefore, frost columns which break down soil cohesion must be listed among the principal causes along with the moisture factors. Although frost columns naturally do not occur in the sandy soil of sand dunes, the scattering of sand does occur easily as the single grains can move independently. Nevertheless, the scattering of sand can be prevented by adding appropriate quantities of water because of the moisture content relations discussed earlier. Sand arrestation can be divided according to the causal factors into the following two aspects. In one method, the scattering of sand is left untreated while the directional magnitude of wind is altered artificially to prevent the invasion of a given area by blown sand. In the other method, active measures are taken with the frictional and cohesive forces of the sand, whereby the scattering is prevented by augmenting these forces.

Sand arrestation in the past has mostly involved the former /165
method except in the case of roads and streets, but the author would strongly assert that the latter method should not be regarded too lightly depending on the locale.

One must of course avoid the mistake of plunging blindly into applications to natural terrains on the basis of a mere small-scale experiment, but one must also be careful of the ignorance of denying the importance of studying the feasibility of such applications. The question hinges on whether or not the investigation is being advanced rationally.

Apart from the abundance or lack of water supply and the temperature range, the following points of difference must necessarily be taken into consideration when comparing the experimental situation to natural terrains.

1) size of surface area
2) consistency or lack of consistency in terms of wind wind velocity and wind direction
3) variation in terrain

The size of the surface area is related to the evaporation rate. This would mean that when the area is large,the evaporation rate per unit area becomes low so that a prolongation of the duration up to the critical sand scattering point would occur. As long as there is no change in the wind direction and velocity, such a cause not only would not present any cause for invalidating Eq. (2), it would also have to be considered as quite promising.

However, since the wind velocity and wind direction are not always constant in nature, the conditions would be rather different from the inside of the laboratory. It is therefore necessary to conduct preliminary studies on the local basis regarding such factors as the impact force of gust or the velocity of wind in the state of conflux in narrow terrains. The equivalent wind velocity corresponding to this force may be assumed to be 2-3 times the normal wind velocity, while the critical moisture content necessary for preventing the scattering of sand exposed to such a velocity can be relatively small, judging from the experimental results. This is because the slope of the straight line representing the relation between the critical wind velocity and the moisture content of sand is quite steep. Consequently, it can be anticipated that the uncertainty over the inconsistency of the wind velocity and the wind direction may be resolved by increasing the critical moisture content by a slight quantity.

The variation in the terrain is also an important element, but with sandy terrains there is practically no need to consider bluffs or cliffs. It is however necessary to conduct adequate preliminary surveys regarding undulations of the terrain and, as mentioned already, the changes in wind force in narrow wind passages.

In fact, it is reported that water sprinkling based on such an approach was adopted on a small scale by farming households in the Hamamura Hot Springs area in Tottori Prefecture for their farmland with a considerable amount of success. Since it would suffice in such cases to maintain the required moisture content down to a shallow depth below the ground surface, it would be possible to put this method into practice with a certain degree of rationality if the durations of interruption are also adopted on the basis of composite time curves obtained from experiments using various wind velocities.

For the water supply, fresh water is better than sea water. This is because fresh water is superior to sea water from the combined standpoint of the prevention of blown sand and the stimulation of the sprouting and growth of vegetation. The underground piping system or the spray system would be suitable for the intermittent sprinkling method, but the problem ultimately is in what manner water can be obtained economically.

To sum up, it is possible to prevent blown sand completely by supplying water, but there is a need to conduct a considerable number of outdoor experiments and to consider local economic situations so the range of feasibility can be determined on a practical level.

V. Conclusions

The following conclusions can be drawn from the results of experiments in the laboratory discussed so far.

1. There is a linear relation between the sand moisture content and the critical wind velocity at which sand grains begin to move.

2. There is a parabolic functional rëlation between the critical force of frictional adhesion and the sand moisture content. /166

3. There is a type of hyperbolic relation between the time duration required for the blown sand phenomenon to occur starting from a fixed moisture content and the critical wind velocity. With wind velocities of 7±10 m/sec as the boundary, the time curve slope becomes very mild below that level.

4. Conclusions 1, 2, and 3 are applicable to grains with eroded corners such as beach sand, but cannot be applied directly to noneroded grains such as clay.

5. Temperature and humidity affect the time curve mentioned in conclusion 3., but the degree of influence is more prominent for a low wind velocity than for a high velocity.

6. The sand arrestation method using a water supply seems to be technically quite feasible, but its practical value must be determined through experiments which also take into consideration the economic situations regarding natural terrains.

VI. Appended Tables [A], [B], and [C], and Appended Figures

[Notes] 1. $[A]_1$, $[A]_2$,... etc are experiment identification numbers.

2. Such entries as 6-7-20 and 6-7-21 next to the experiment identifications numbers indicate the date of each experiment. For example, the two entries above respectively represent July 20, Shōwa 6 [1931] and July 21, Shōwa 6.

3. Notations in the tables

(a) = weather (b) = temperature (c) = humidity

(d) = initial moisture content (e) = height of container

: measured moisture content in % (with respect to the dry sand) in the moment sand is scattered

W_1: measured critical wind velocity m/sec

W: critical wind velocity calculated from experimental equation m/sec

T: time duration from start of experiment to occurrence of blown sand phenomenon (minutes)

Tables of Moisture Content Curves [A],[B]

$[A]_1$ July 20, 1931

(a) = rain (b) = 23.5°C (c) = 92%

(d) = Without the use of a container, the sand was piled on a glass plate to the height of 1.5 cm. Sand from the surface to the depth of 2.5 mm was sampled and weighed.

$W=5.360\alpha-2.090$

α	W_1	W	W_1-W
3.200	14.60	15.0642	− 0.4642
2.710	12.20	12.4373	− 0.2373
2.370	10.80	10.6147	+ 0.1853
2.000	8.66	8.6311	+ 0.0289
1.450	6.17	5.6827	+ 0,4873

$[A]_2$ July 21, 1931

(a) = cloudy (b) = 22.2°C

(c) = 90% (d) = 5 mm

$W=5.22\alpha+0.98$

α	W_1	W	W_1-W
2.770	15.40	15.4319	− 0.0319
2.360	13.30	13.2925	+ 0.0075
1.860	10.80	10.6835	+ 0.1165
1.560	9.03	9.1181	− 0.0881

Fig. 6

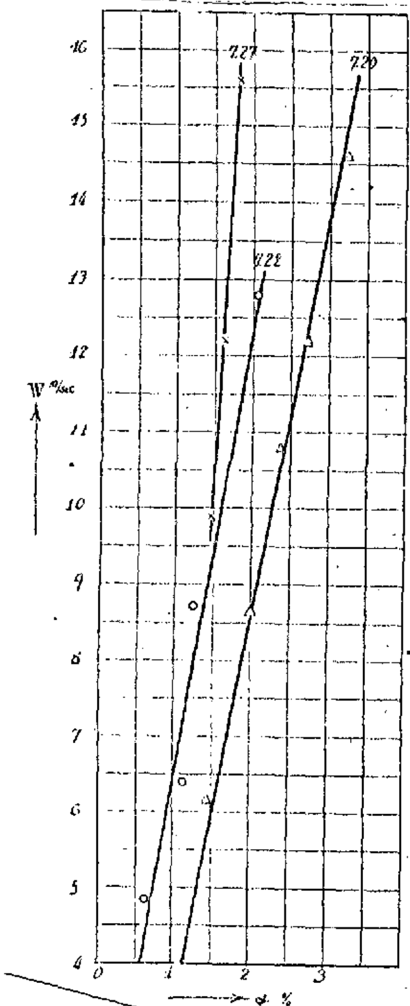


Fig. 7

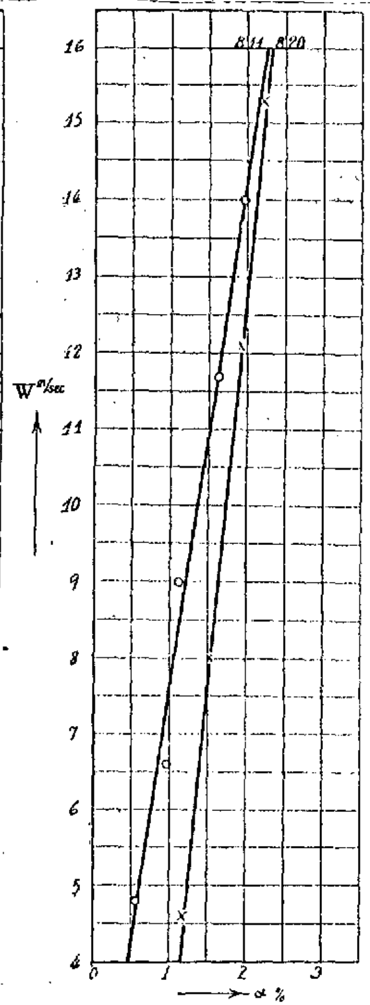


Fig. 8

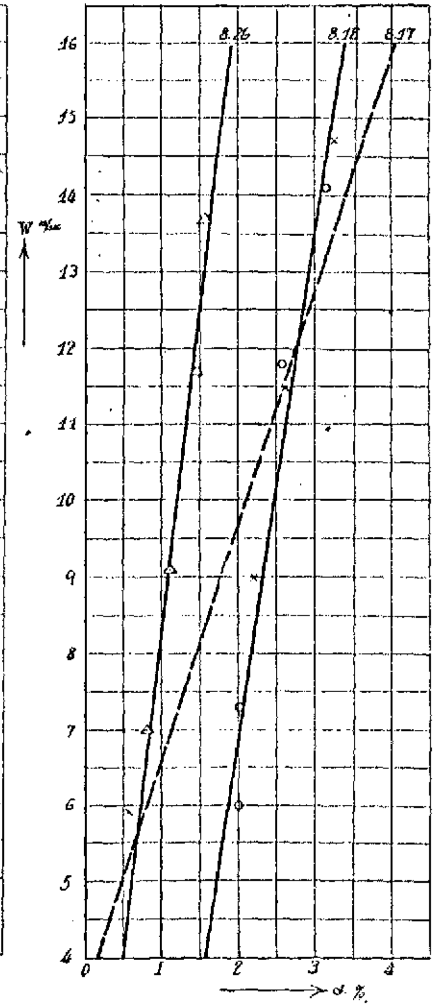
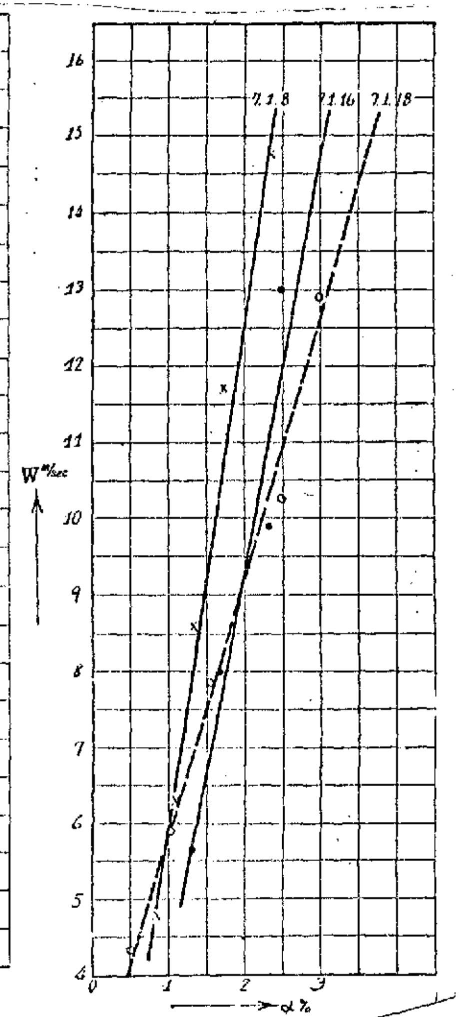


Fig. 9



Appended Figures of Moisture Content Curves $W = a\alpha + b$

$[A]_3$ July 22, 1931

(a) = rain (b) = 19.8°C

(c) = 90% (d) [blank]

(e) = 5 mm

$W=5.73\alpha+0.95$			
α	W_1	W	W_1-W
2.060	12.81	12.7487	+ 0.0613
1.250	8.73	8.1091	+ 0.6209
1.120	6.40	7.3644	− 0.9644
0.630	4.84	4.5577	+ 0.2823

$[A]_4$ July 23, 1931

(a) = cloudy (b) = 21.0°C

(c) = 83.5% (d) [blank] (e) = 5 mm

$W=4.214\alpha+1.086$			
α	W_1	W	W_1-W
2.440	11.50	11.3689	+ 0.1311
1.580	7.45	7.7445	− 0.2945
0.890	5.00	4.8366	+ 0.1634

$[A]_5$ July 26, 1931

(a) = cloudy (b) = 26.0°C

(c) = 88% (d) [blank]

(e) = 5 mm

$W=4.07\alpha+3.936$			
α	W_1	W	W_1-W
2.928	15.28	15.8599	− 0.5799
2.254	14.10	13.1152	+ 0.9848
1.836	11.30	11.4129	− 0.1129
1.077	8.03	8.3220	− 0.2920

$[A]_6$ July 27, 1931

(a) = cloudy (b) = 26.2°C

(c) = 84.5% (d) [blank]

(e) = 5 mm

$W=16.617\alpha-15.00$			
α	W_1	W	W_1-W
1.805	15.60	15.5269	+ 0.0731
1.618	12.20	12.3637	− 0.1637
1.467	9.90	9.8094	+ 0.0006

$[A]_8^{(I)}$ July 29, 1931

(a) = cloudy, clear (b) = 25.8°C

(c) = 76% (d) [blank]

(e) = 5 mm

$W=2.098\alpha+3.203$			
α	W_1	W	W_1-W
3.370	10.30	10.2738	+ 0.0262
2.160	7.70	7.7351	− 0.0351
0.385	4.03	4.0111	+ 0.0189

$[A]_9^{(I)}$ July 31, 1931

(a) = clear, cloudy (b) = 27.2°C

(c) = 81% (d) [blank]

(e) = 3 mm

$W=5.841\alpha+2.349$			
α	W_1	W	W_1-W
1.98	14.30	13.9141	+ 0.3859
1.40	9.80	10.5265	− 0.7265
0.56	6.48	5.6201	+ 0.8599
0.44	4.40	4.9192	− 0.5192

$[A]_8^{(II)}$ July 29, 1931

(a) = clear, cloudy (b) = 25.8°C

(c) = 76% (d) [blank]

(e) = 5 mm

$W=1.803\alpha+3.735$

α	W_1	W	W_1-W
3.370	10.30	9.8117	+ 0.4883
2.160	7.70	7.6299	+ 0.0701
2.340	7.20	7.9544	− 0.7544
0.205	4.70	4.1047	+ 0.5953
0.385	4.03	4.4293	− 0.3993

$[A]_9^{(II)}$ July 31, 1931

(a) = clear, cloudy (b) = 27.2°C

(c) = 81% (d) [blank]

(e) = 3 mm

$W=6.233\alpha+1.860$

α	W_1	W	W_1-W
2.120	16.30	15.0822	+ 1.2178
1.980	14.30	14.2095	+ 0.0005
1.380	12.15	10.4996	+ 1.6804
1.400	9.80	10.5942	− 0.7942
1.450	7.80	10.9059	− 3.1059
0.560	6.48	5.3583	+ 1.1217
0.440	4.40	4.6103	− 0.2103

$[A]_{10}^{(I)}$ August 1, 1931

(a) = clear (b) = 26.5°C

(c) = 90.5% (d) = 25%

(e) = 3 mm

$W=11.189\alpha-3.842$

α	W_1	W	W_1-W
1.680	15.30	14.9559	− 0.3441
1.340	14.50	11.1516	− 3.3484
1.230	12.10	9.9208	− 2.1792
1.450	9.40	12.3824	+ 2.9824
0.990	8.10	7.2354	− 0.8646
1.180	6.10	9.3613	+ 3.2613
0.870	5.40	5.8927	+ 0.4927

$[A]_{11}^{(I)}$ August 3, 1931

(a) = clear (b) = 27°C

(c) = 70.6% (d) = 25% (e) = 3 mm

$W=9.503\alpha-1.267$

α	W_1	W	W_1-W
1.540	15.30	13.3758	+ 1.9242
1.590	13.30	13.8513	− 0.5513
1.270	11.00	10.8086	+ 0.1914
1.370	9.10	11.7594	− 2.6594
0.960	7.35	7.8610	− 0.5110
0.690	5.70	5.2938	+ 0.4062

$[A]_{10}^{(II)}$ August 1, 1931

(a) = clear (b) = 26.5°C

(c) = 90.5% (d) = 25%

(e) = 3 mm

$W=11.767\alpha-3.842$

α	W_1	W	W_1-W
1.68	15.3	15.9758	− 0.6758
1.23	12.1	10.6674	+ 1.4326
0.99	8.1	7.8362	+ 0.2638
0.87	5.4	6.4206	− 1.0206

$[A]_{11}^{(II)}$ [No date given]

(a) = clear (b) = 27°C

(c) = 70.6% (d) = 25%

(e) = 3 mm

$W=9.180\alpha-0.713$

α	W_1	W	W_1-W
1.59	13.30	13.3834	− 0.5834
1.27	11.00	10.9457	+ 0.0543
0.96	7.35	8.0998	− 0.7498
0.67	5.70	5.6211	+ 0.0789

[A]$_{12}$ Augustt7, 1931

(a) = cloudy, then clear
(b) = 30°C (c) = 59.8%
(d) = 25% (e) = 3 mm

$W = 5.646\alpha + 2.512$

α	W_1	W	$W_1 - W$
1.510	16.50	11.0383	+ 5.4617
1.500	13.00	10.9818	+ 2.0182
1.460	11.00	10.7560	+ 0.2440
1.610	9.20	11.6029	− 2.4029
1.170	7.20	9.1186	− 1.9186
1.350	5.90	10.1349	− 4.2349
0.240	4.70	3.8675	+ 0.8325

[A]$_{13}$ August 2, 1931

(a) = clear (b) = 28°C
(c) = 76% (d) = 25% (e) = 3 mm

$W = 8.790\alpha - 0.687$

α	W_1	W	$W_1 - W$
1.780	14.60	14.9585	− 0.3585
1.050	10.50	8.5420	+ 1.9580
0.990	8.30	8.0146	+ 0.2854
0.910	6.90	7.3114	− 0.4114
0.900	5.75	7.2235	− 1.4735

[A]$_{14}$ August 11, 1931

(a) = cloudy (b) 27°C
(c) = 81% (d) 25% (e) = 3 mm

$W = 6.628\alpha + 0.908$

α	W_1	W	$W_1 - W$
1.970	14.00	13.9658	+ 0.0342
1.640	11.70	11.7785	− 0.0785
1.120	9.00	8.3318	+ 0.6682
0.980	6.60	7.4039	− 0.8039
0.560	4.80	4.6200	+ 0.1800

[A]$_{15}$ August 17, 1931

(a) = clear (b) 28°C (c) = 75%
(d) = 25% (e) = 3 mm

$W = 3.094\alpha + 3.568$

α	W_1	W	$W_1 - W$
3.270	14.70	13.6863	+ 1.0137
2.630	11.50	11.7060	− 0.2060
2.210	9.00	10.4065	− 1.4065
0.560	5.90	5.3012	+ 0.5988

[A]$_{16}$ August 18, 1931

(a) = clear (b) = 28°C
(c) = 65% (d) 27.25% (e) = 3 mm

$W = 6.653\alpha - 6.435$

α	W_1	W	$W_1 - W$
3.1656	14.10	14.6267	− 0.5267
2.5844	11.80	10.7598	+ 1.0402
2.01257	7.30	6.9552	+ 0.3448
1.9980	6.00	6.8583	− 0.8583

[A]$_{17}$ August 20, 1931

(a) = cloudy (b) 27°C (c) = 73%
(d) = 20% (e) = 3 mm

$W = 10.173\alpha - 7.471$

α	W_1	W	$W_1 - W$
2.220	15.30	15.1117	+ 0.1883
1.940	12.10	12.2634	− 0.1634
1.540	8.00	8.1944	− 0.1944
1.170	4.60	4.4305	+ 0.1695

[A]$_{18}$ August 26, 1931
(a) = cloudy (b) 26.5°C
(c) = 82% (d) 25%
(e) = 3 mm

$W = 8.454\alpha - 0.003$

α	W_1	W	$W_1 - W$
1.550	13.70	13.1016	+ 0.5984
1.450	11.70	12.2562	− 0.5562
1.110	9.10	9.3816	− 0.2816
0.800	7.00	6.7607	+ 0.2393

[B]$_1$ January 8, 1932
(a) = cloudy (b) = 17°C (c) =
63-66% (d) 25% (e) = 3 mm

$W = 6.550\alpha - 0.368$

α	W_1	W	$W_1 - W$
2.355	14.5	15.0562	− 0.5562
1.707	11.7	10.8119	+ 0.8881
1.304	8.6	8.1727	+ 0.4273
1.095	6.3	6.8038	− 0.5038
0.828	4.8	5.0551	− 0.2551

[B]$_2$ January 16, 1932
(a) = cloudy (b) = 4-8°C
(c) = 50-63% (d) = 22%
(e) = 3 mm

$W = 5.369\alpha - 1.298$

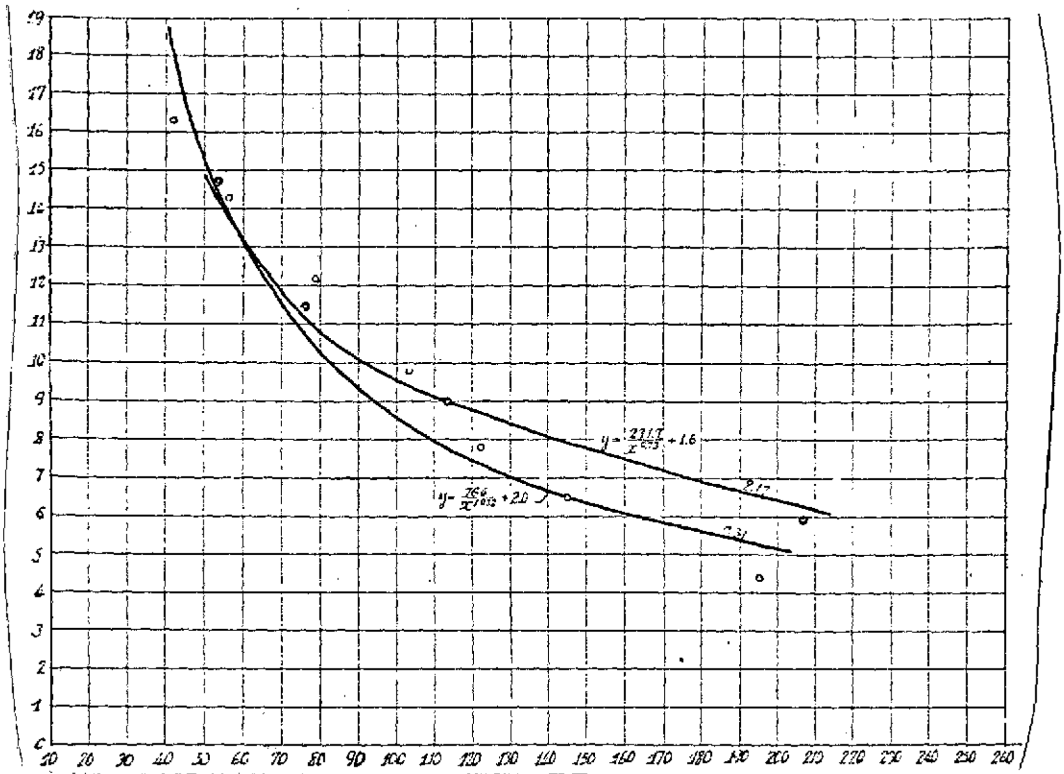
α	W_1	W	$W_1 - W$
2.495	13.0	11.90	+ 1.0962
2.337	9.9	11.24	− 1.3488
1.666	8.0	7.65	+ 0.3537
1.313	5.65	5.75	− 0.1011

[B]$_3$ January 18, 1932
(a) = cloudy (b) = 6.5-13°C
(c) = 55.5-56.3% (d) = 22%
(e) = 3 mm

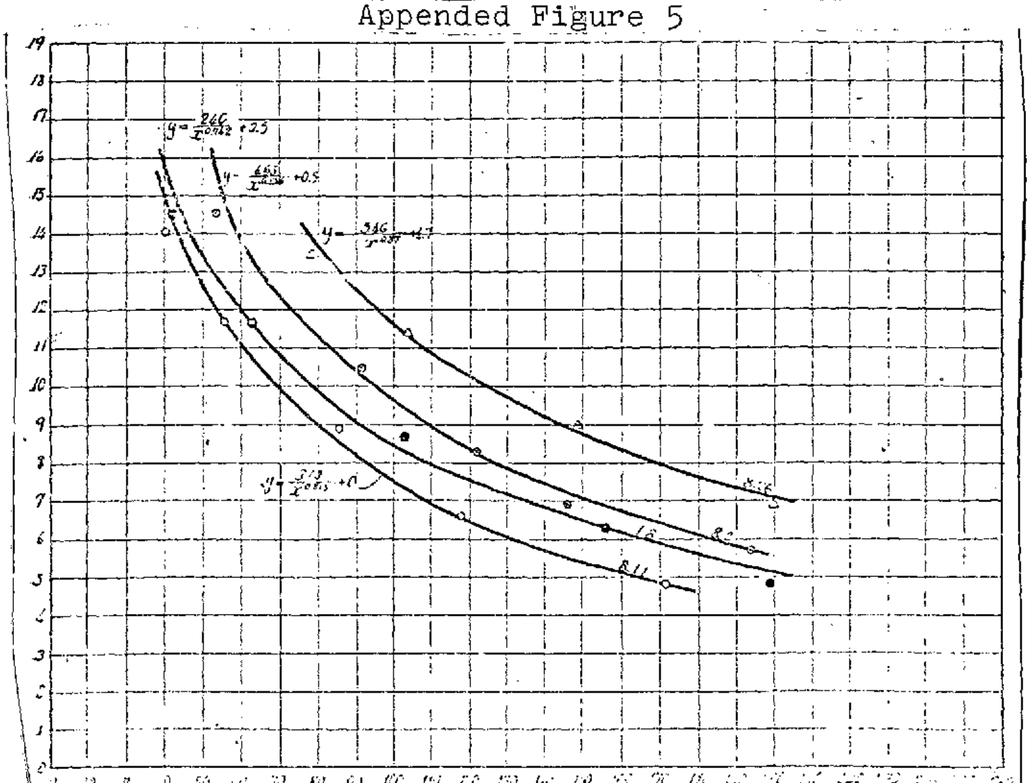
$W = 3.247\alpha + 2.397$

α	W_1	W	$W_1 - W$
2.985	12.9	12.627	+ 0.2730
2.448	10.25	10.7865	− 0.5665
1.546	7.85	7.6952	+ 0.1548
1.035	5.88	5.9439	− 0.0639
0.5196	4.35	4.1775	+ 0.1725

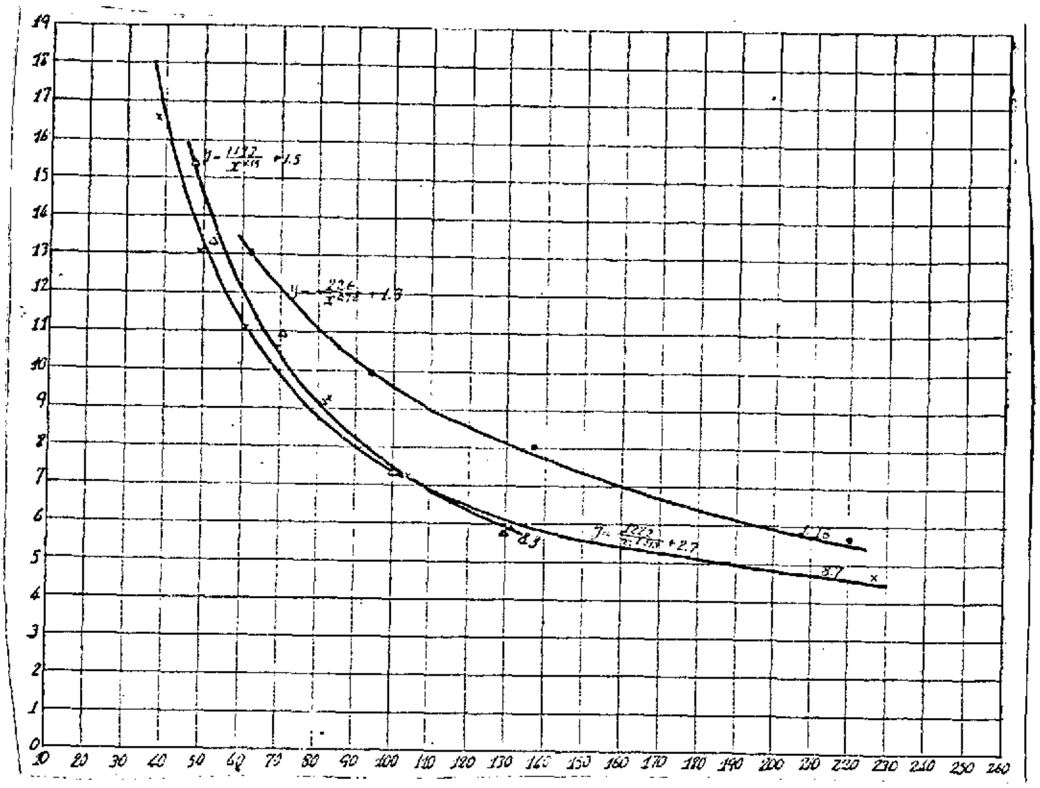
Time curves of $W=\frac{K_1}{T^m}+K_2$



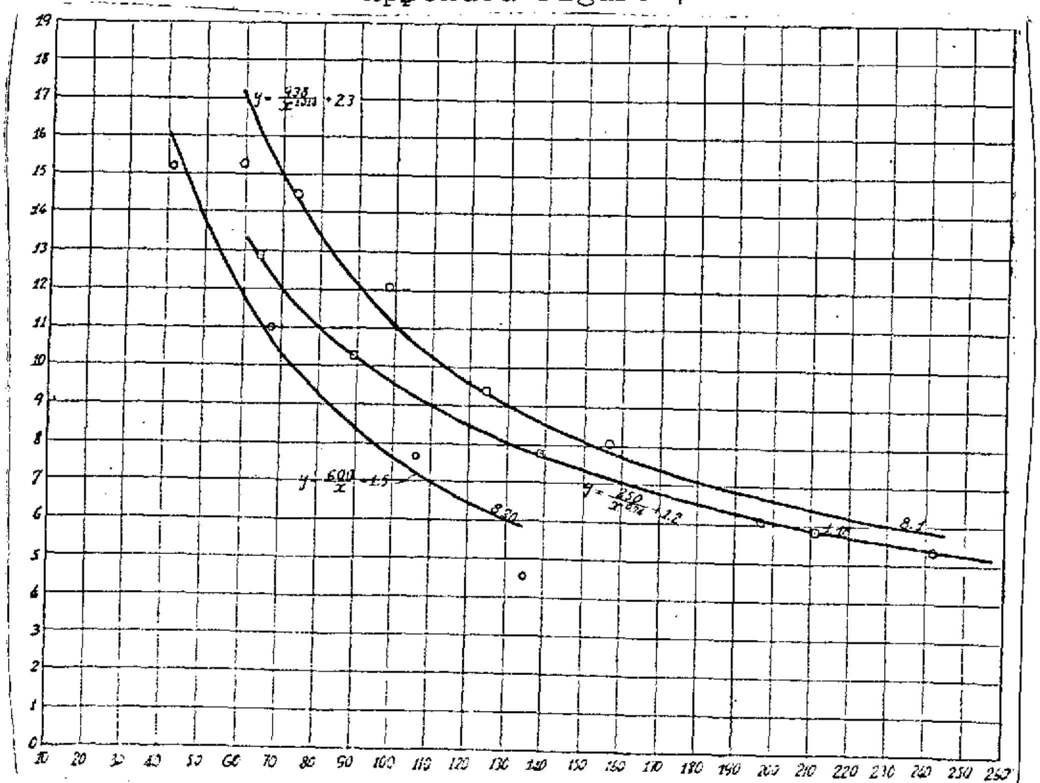
Appended Figure 5



Appended Figure 6



Appended Figure 7



Appended Figure 8

$[C]_1$ July 31, 1931

(a)

$$W=\frac{764}{T^{1\cdot032}}+2.0$$

W_1	T	W	W_1-W
16.3	42.0	18.2	− 1.9
14.3	56.0	14.0	+ 0.3
12.15	78.0	10.5	+ 1.65
9.8	103.0	8.4	+ 1.4
7.8	122.0	7.4	+ 0.4
6.48	145.0	6.5	− 0.02
4.4	195.0	5.3	+ 0.9

$[C]_2$ August 1, 1931

$$W=\frac{398}{T^{1\cdot014}}+2.3$$

W_1	T	W	W_1-W
15.3	59.5	17.2	− 1.9
14.5	73.0	14.4	+ 0.1
12.1	98.0	11.3	+ 0.8
9.4	124.0	9.4	0
8.1	156.0	7.9	+ 0.2
6.1	196.0	6.8	− 0.7
5.4	242.0	5.9	− 0.5

$[C]_3$ August 2, 1931

$$W=\frac{465}{T^{0\cdot854}}+0.5$$

W_1	T	W	W_1-W
14.6	54.5	15.8	− 1.2
10.5	91.4	10.32	+ 0.18
8.3	122.0	8.18	+ 0.12
6.9	146.0	7.09	− 0.19
5.75	194.0	5.67	+ 0.08

$[C]_4$ August 3, 1931

$$W=\frac{1173}{T^{1\cdot15}}+1.5$$

W_1	T	W	W_1-W
15.3	47	15.5	− 0.2
13.3	51	14.2	− 0.9
11.0	71	10.2	+ 0.8
9.1	81	8.9	+ 0.2
7.35	100	7.4	− 0.05
5.7	129	5.9	− 0.2

$[C]_5$ August 7, 1931

$$W=\frac{1222}{T^{1\cdot213}}+2.7$$

W_1	T	W	W_1-W
16.5	38.0	17.50	− 1.00
13.0	48.5	13.72	− 0.72
11.0	61.5	10.97	+ 0.03
9.2	83.0	8.45	+ 0.75
7.2	103.0	7.12	+ 0.08
5.9	132.0	5.98	− 0.08
4.7	227.0	4.40	+ 0.30

$[C]_6$ August 11, 1931

$$W=\frac{313}{T^{0\cdot815}}+0$$

W_1	T	W	W_1-W
14.0	41	15.10	− 1.10
11.7	56	11.76	− 0.06
9.0	86	8.30	+ 0.70
6.6	117	6.48	+ 0.12
4.8	172	4.7	+ 0.10

$[C]_7$ August 17, 1931

$$W = \frac{231.7}{T^{0.73}} + 1.6$$

W_1	T	W	$W_3 - W$
14.7	53	14.4	+ 0.3
11.5	76	11.4	+ 0.1
9.0	113	9.0	0
5.9	207	6.3	− 0.4

$[C]_8$ August 20, 1931

$$W = \frac{600}{T^{1.00}} + 1.5$$

W_1	T	W	$W_1 - W$
15.3	41	16.1	− 0.8
12.1	67	10.5	+ 1.6
8.0	106	7.2	+ 0.8
4.6	134	6.0	− 1.4

$[C]_9$ August 26, 1931

$$W = \frac{546}{T^{0.87}} + 1.7$$

W_1	T	W	$W_1 - W$
13.7	78	14.03	− 0.33
11.7	104	11.30	+ 0.40
9.1	149	8.73	+ 0.37
7.0	200	7.10	− 0.10

$[C]_{10}$ January 8, 1932

$$W = \frac{240}{T^{0.742}} + 0.5$$

W_2	T	W	$W_1 - W$
14.5	42.5	15.3	0.8
11.7	62.5	11.7	0
8.6	103.0	8.2	+ 0.4
6.3	156.0	6.2	+ 0.1
4.8	199.0	5.2	− 0.4

$[C]_{11}$ January 18, 1932

$$W = \frac{250}{T^{0.74}} + 1.2$$

W_1	T	W	$W_1 - W$
12.9	63	12.9	0
10.3	89	10.2	+ 0.10
7.85	139	7.7	+ 0.15
5.88	211	6.0	− 0.12
4.35	292	5.0	− 0.65

$[C]_{12}$ January 16, 1932

$$W = \frac{226}{T^{0.72}} + 1.3$$

W_1	T	W	$W_1 - W$
13.0	62	12.9	+ 0.10
9.9	94	9.9	0
8.0	137	7.8	+ 0.20
5.65	220	6.0	+ 0.35

(Manuscript received on May 10, 1933).

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